ALLISON ENGINE COMPANY'S INDUSTRIAL ADVANCED TURBINE SYSTEMS PROGRAM OVERVIEW

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INTRODUCTION

The U.S. Department of Energy (DOE) and the gas turbine industry conceived a partnership in the Advanced Turbine Systems (ATS) Program that would serve the needs of the country by developing gas turbine systems to provide high efficiency, environmentally friendly, and cost effective sources of electricity. As we begin the third year of the ATS Program serving this need becomes ever so close to a reality.

OBJECTIVE

Allison's overall program objective is to design, develop, and demonstrate a simple cycle gas turbine system with 40% thermal efficiency at 13.5 MW. This objective will be achieved while providing emissions performance levels of less than 9 parts per million (ppm) oxides of nitrogen (NO_x), 20 ppm carbon monoxide (CO), and unburned hydrocarbons (UHC). This will be achieved with improvements in reliability, safety, and durability. Development of the gas turbine system is occurring concurrently with the generator package, with the objective of offering lower system capital costs and operating costs.

Allison's primary objective over the past year has focused on the design of the major gas turbine engine modules and integration of the gas turbine engine with the overall generator system. Teams of engineers have been working to define engine module configurations meeting the efficiency and emission goals, and still meeting the aggressive manufacturing cost and durability requirements. Near-term program objectives over the past year focused on evaluating and implementing technologies central to the success of the Allison industrial ATS. These specific objectives include:

- Definition of catalytic combustion element operating parameters at the aggressive ATS operating conditions

- Evaluation of catalyst durability

- Combustion rig design, fabrication, and testing to effectively evaluate performance of major combustion system elements and the integration of these elements

- Evaluation and selection of the most cost effective material/design approaches for the most technically challenging portions of the engine

- Engine and generator drive line definition

APPROACH

The overall efficiency and emission objectives will be achieved by leveraging the advanced aero engine technologies and industrial combustion component technologies that Allison and the U.S. Government partners, both the DOE and the Department of

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Defense (DOD), have invested in over the recent past. These technologies will be applied to a gas turbine system that from its inception is designed with the express purpose of providing a state-of-the-art industrial ATS. This path will yield a high performance and cost effective industrial package, and is unique, since it is not a traditional industrial aero derivative gas turbine approach.

System Efficiency Design Approach

To achieve the overall thermal efficiency goal of 40%, the system design must build upon a solid base of component technologies having high efficiencies. These components must then be arranged/matched based upon demonstrated component performance levels, anticipated improvements in performance, and the thermal/structural demands presented by the overall engine cycle. The Allison ATS will achieve this system efficiency by striking a balance between the overall system pressure ratio and the turbine firing temperature. As with any gas turbine, the ability to achieve system efficiency goals begins with the compressor performance. The ATS will capitalize on the aerodynamics designed and developed for the AE family of Allison aero engines. This provides a low risk approach to a high efficiency, high pressure compressor by virtue of the millions of dollars invested in development, the years of development experience and testing, and the demonstrated performance in production applications. All other aerodynamic components are within demonstrated capabilities and experience, so the risk of achieving the overall component efficiency levels, and thus the overall system thermal efficiency, is low.

System Emissions Design Approach

The exterior profile of the ATS engine is shown in Figure 1. To meet the emissions

Figure 1. Exterior profile of ATS engine showing silo combustion system.

goals the combustion system design is configured as an external silo combustor mounted perpendicularly to the centerline of the engine. The single silo combustor approach maximizes combustion volume available for the given liner and transition duct surface area to maximize combustor residence time and minimize liner wall cooling flow. In this arrangement, compressor airflow is discharged into a short annular diffuser section prior to being dumped into a cavity located at the center of the engine. An annular opening in the engine case routes airflow around a single silo combustion chamber. The combustion chamber is segmented into combustion zones for optimal emission performance. The resultant high temperature combustion gas is guided into the turbine through a combustor-to-turbine transition duct, which turns and redirects the flow into the gas generator turbine.

The staged, catalytic combustion system is shown schematically in Figure 2. This combustion system has distinct lean premix and catalytic combustion features to permit stable combustor performance over the engine operational range. The lean premixed
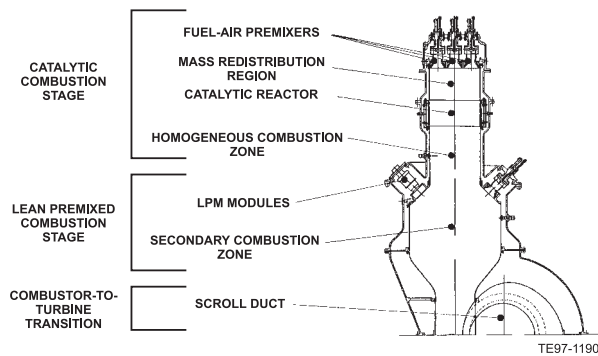
Figure 2. ATS staged combustion system.

combustion region alone provides stable engine operation from idle to approximately half-maximum power. During this idle-to-part power engine operation, lean premix modules (LPMs) are fueled sequentially to produce the required temperature rise and emission profile. As engine load increases, the compressor discharge temperature rises to a level that will sustain the catalytic combustion stage. At this point, fuel is apportioned between the catalytically supported combustion and lean premixed combustion to accelerate the engine from part load to demanded load. This approach makes effective use of the elevated compressor discharge temperature to support catalytic combustion without the need for preheating the gas mixture as it enters the catalytic element. Fundamentally, the catalytic surface will only become active and begin to convert the fuel-air mixture to products after a threshold inlet temperature is reached. In the present approach, no flame is present upstream of the catalyst that might cause damage to the catalytic reactor element. The catalytic stage of the combustion system can be segregated into three functional zones. First, the catalytic premixing zone produces an ultra-lean premixed fuel-air mixture upstream of a catalytic reactor. The catalytic reactor zone (Figure 2) then converts a portion of the fuel to products of combustion and raises the bulk temperature of the flow. Lastly, flow leaving the reactor enters a postcatalytic,

homogenous combustion zone where the balance of the reactants are converted to combustion products through a spontaneous ignition process. A secondary combustion zone is located aft of the catalytic stage. In this secondary stage, fuel-air premixers are arranged around the periphery of the combustor and establish a flow field for flame stabilization of the mixture exiting the individual premixers. The flow from the lean premixed stage then interacts with the flow exiting the catalytic stage. This approach provides flexibility in fuel staging between lean premixed and catalytically stabilized combustion zones to permit better idle-to-maximum power operation.

PROJECT DESCRIPTION

The Allison industrial ATS Program is a cooperative effort with the U.S. DOE aimed at developing ultra-high efficiency and clean sources of electrical energy. Allison's $82.5 million full-scale development program was initiated in late 1995. The program includes design of a +40% simple cycle thermal efficiency gas turbine, design of a new centerline generator package, rig and engine system integration testing, and a field demonstration test.

The gas turbine system is configured as a three-shaft engine for optimum efficiency. This high pressure ratio engine has a 3-stage, low pressure compressor matched with a 12-stage, high pressure (HP) compressor to provide a overall pressure ratio of 30:1. The engine includes a single can, silo combustion system, offset from the engine centerline to allow flexibility in the system design at the aggressive operating conditions to meet both gas and liquid fuel dry low emissions requirements. The hot section will achieve life requirements at firing temperatures up to 2600°F. The initial field demonstration will be conducted at 2400°F, with power output

provided by a hot end drive, two-stage, industrial power turbine.

The Allison industrial ATS will be marketed as the Allison 701-K. Initial commercial offerings will resemble the industrial ATS demonstration configuration and range in power from 9 to 13 MW. The 701-K will be adaptable to mechanical drive and marine applications. The initial field demonstration is slated for the year 2000, with commercial product availability beginning in 2001.

The generator package is being designed and developed by U.S. Turbine (UST) located in Maineville, Ohio. Concurrent package design and development is in progress to optimize efficiency, capital cost, and operating cost for the engine, generator package, and supporting systems.

RESULTS

Combustor Operation

Figure 3 shows preliminary staging details with accompanying combustion zone temperatures, and NO_x predictions over the range of engine operation for a series staged, catalytically stabilized combustion system. The combustion in the catalytic and lean premixed zones is staged by careful selection of local stoichiometry at any given operating condition. At idle conditions, all of the fuel is consumed in the lean premixed combustion zone. Since limited heat release is required, the combustion is localized to a small fraction of the combustion chamber and the temperature (T2) is maintained at a level near 3000°F or less. As higher combustor discharge firing temperatures are required, more of the LPMs are supplied with fuel and the lean premixed combustion zone expands to include a greater volume within the chamber. At 50% load, the compressor discharge temperature reaches a level
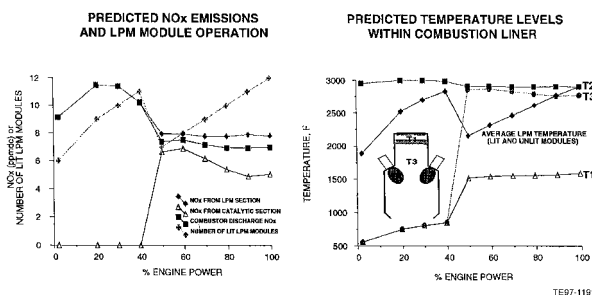

Figure 3. Combustion operation from idle-to-maximum power showing NO_X predictions and local temperatures.

sufficient to activate the catalyst, at which time a portion of the fuel is routed into the catalytic fuel injectors. Concurrently, the fuel flow and number of LPM combusting zones are decreased. As load is increased further, the fraction of fuel delivered to the catalyst is reduced and additional LPM combusting zones are introduced. This maintains a constant temperature of approximately 930 K (1550°F) at the discharge of the catalytic reactor, so the reactor substrate material does not suffer from thermal distress. The NO_x emissions shown in Figure 3 are estimated from the data obtained from Allison's LPM combustion and subscale catalytic combustion tests. The staging between catalytic and LPM combusting zones affords low NO_x emissions over a wide range of engine power settings while satisfying the 9 ppm ATS NO_x goals at maximum power.

Catalytic Combustion Design and Development

Catalytic design and development is being performed by Catalytica of Mountainview, California. Over the past year Catalytica has concentrated on catalyst designs for the Allison ATS, basic research in the area of catalyst durability, test rig preparation and testing to support performance and mechanical integrity evaluations, and catalyst fabrication.

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Initial design and rig test evaluations concentrated on the development of a catalyst composition with an operational window acceptable for Allison's initial high pressure rig testing. This catalyst is designed to achieve the desired performance level at 18 atmospheres and 1000°F temperature inlet conditions. An acceptable design was fabricated and tested in a subscale test at Catalytica. A larger 8-in. diameter catalyst has been fabricated for Allison combustion rig testing in November 1997.

Other accomplishments over the past year include:

- Evaluation of the catalyst's tolerance to a salt laden air environment
- Testing of catalyst performance in the presence of engine oils
- Thermal cyclic fatigue rig design and fabrication

Postcatalytic Combustion Zone

To properly design the postcatalytic homogeneous reaction zone it is important to predict the ignition delay times and provide adequate residence time for the reaction to be completed within this zone to limit CO and UHC emissions. A reaction taking place too quickly will occur too close to the catalyst and durability will be a concern.

Experimental ignition delay data have been generated in a catalytic subscale reactor with operating pressure up to 20 atm. Kinetic modeling has been performed in an attempt to predict ignition delay times in the postcatalytic zone. Comparisons between the analytical and empirical data at common conditions will allow extrapolation to other pressures and temperatures with some confidence.

Lean Premix Module Development

The LPM must be capable of premixing the incoming fuel-air mixture and creating a stabilizing region to anchor the flame over a wide range of pressure, temperature, and stoichiometric conditions. Additionally, flashback must be avoided and low NO_x emissions maintained.

Figure 4 is a schematic representation of the basic LPM developed for Allison's 501-K engine. Air enters into the premixer through a radial swirler positioned directly aft of a fuel distribution manifold. A fuel distribution tube, with a series of holes along its length, is positioned in the center of the passage formed between the swirler vanes. The nozzle throat functions to separate the premixing section from the combusting section. As the premixed reactants exit the throat, they enter a divergent section producing a controlled central recirculating flow that stabilizes a flame at the discharge of each LPM.

A parametric study was conducted on the baseline radial swirler plus nozzle (RSPN) module to determine its sensitivity to flashback at ATS conditions. The expansion of the flow aft of the throat produces a flow field in which the axial centerline velocity is
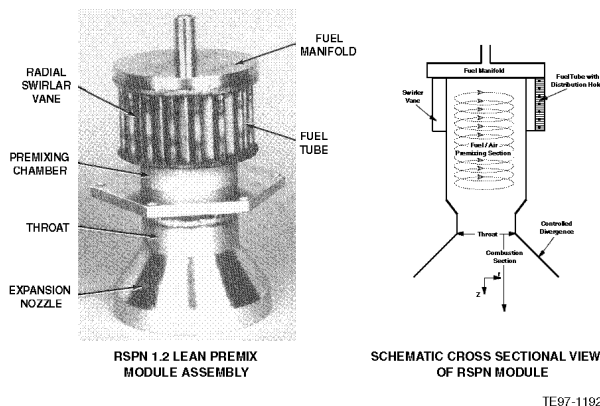

Figure 4. Radial swirler plus nozzle lean premix module.

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low prior to formation of the recirculation zone. The propensity of the flame to flashback into the premixer is greatest at this location where the axial velocity is minimized. A series of design options were considered and analyzed with a 2-D computational fluid dynamic (CFD) code. The focus of this effort was to identify potential designs impacting flame propagation velocity by adjusting the stoichiometry locally to match the velocity field. In conjunction with the analytical effort, individual LPM swirler designs were bench tested at atmospheric conditions to determine mixing efficiency and flashback propensity. Based on the analytical and laboratory test results eight LPMs were rapid prototyped for combustion system rig test.

Combustion System Test

The combustion rig shown in Figure 5 has been designed and built to test a scaled version of the ATS silo combustion liner. This scaled version simulates the full-scale combustion series staging configuration with primary and secondary fuel injection and combustion zones. The prototype series stage liner is pictured in Figure 6. The primary zone will be tested with and without catalytic elements. The rig configuration uses 8 fuel injection nozzles (Figure 7) as compared to the 19 nozzles used in the full-scale version. The inlet conditions of the rig simulate the compressor discharge temperature of 1030°F but are limited by facility inlet pressure capability of 18 atmospheres.

The configuration provides evaluation of multiple LPM interactions within a zone and the effects of the series staging
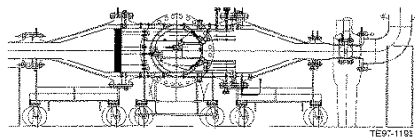

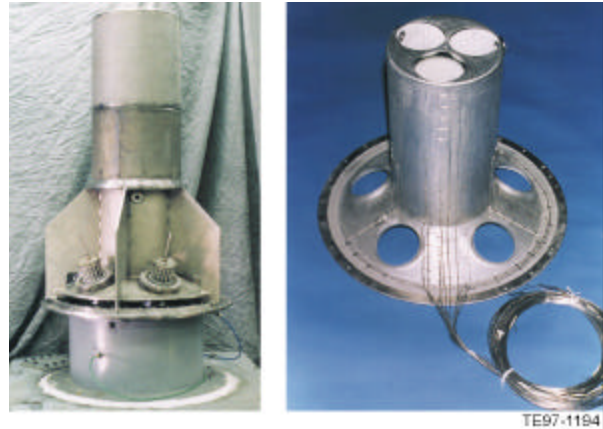*Figure 5. ATS high pressure combustion rig.*

Figure 6. ATS prototype effusion-cooled combustion liner.

Figure 7. ATS rapid prototype lean premix module.

(primary/secondary) between the zones. This scaled version can also provide insight into the effects of staging and transitioning between multiple LPMs. The ignition characteristics of the various combinations of staging can be also be observed. Testing in the combustion rig will provide a means to begin accumulating

empirical emissions data at part and full power operation.

These tests will provide operation of the catalyst on a larger scale and show the performance and effects of the catalyst and LPM interaction. Cooling schemes for the liner can also be evaluated to provide input for the cooling flux requirements and configuration on the full-scale rig and production hardware. Other input for engine design to be derived from this rig testing includes final liner sizing and development of the fuel control staging algorithm.

Initial rig testing of the system, shown installed in the rig in Figure 8, started in September with LPM in both the primary and secondary stages. This testing is being followed with a primary combustion zone test using three premixers and an 8-in. catalytic reactor. Over the next several months parametric testing will be conducted on both configurations. In early 1998 premixers, catalytic reactor, and LPM systems will be integrated into a subscale system test.

Material and Design Challenges

Meeting the demanding conditions of the Allison industrial ATS presents many material
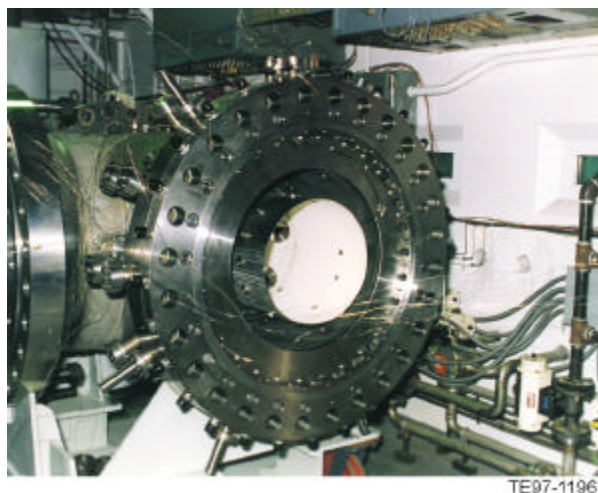

Figure 8. ATS combustion rig.

and design challenges. These demand satisfactory technical solutions, but equally as important, these solutions must be cost effective. The following are examples of several solutions to the challenges.

High Pressure Compressor Blisks: The ATS HP compressor design approach maximizes aerodynamic commonality with the Allison AE family of flight engines. With the addition of the low pressure (LP) compressor to the ATS engine, the inlet pressure conditions to the HP compressor are elevated in comparison to the AE engine family. This results in higher temperatures and pressures at each stage in the compressor. Another factor making the design requirements more rigorous is the addition of mechanical drive and marine application duty cycles.

With these design requirements in mind to meet the life criteria at compressor discharge conditions of approximately 1030°F and 30 atmosphere, nontraditional materials or configurations are needed. Using a conventional approach of separately bladed disks on the last two compressor stages (11 and 12) required expensive alloy such as Udimet 720 to survive the thermal gradients seen during transient operation. As a cost reduction effort, integrally bladed disks (blisks) have been selected for use. This configuration requires a smaller rim, reduces the stress concentration present at the blade attachment, and provides less mass to be supported outboard of the last continuous circumferential fiber. With the lowered stress levels, a lower cost alloy, Waspaloy, can be used.

Machining trials producing an aluminum blisk of an equivalent ATS configuration have been completed at Allison. A subsequent machining trial using Waspaloy material will be performed to substantiate the producibility of the ATS configuration in the production material.

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Combustion Transition Scroll: The combustion transition scroll for the ATS engine is designed to provide a near-uniform velocity profile into the first-stage high pressure turbine vanes. The mechanical design of the scroll requires thermal protection and novel manufacturing approaches to produce the complex geometry of the scroll.

The transition scroll is designed in the shape of a spiral, where the hot gases see a constantly decreasing flow area as they flow through the scroll. From the combustor, the scroll receives heated combustion gases that have been channeled through the funnel piece and turns this vertical flow to horizontal. The flow exits the scroll through a constant width annulus and passes into the first-stage turbine vanes. The exiting flow also has a swirl angle associated with it so the exit flow angle is properly matched to the turbine vane angle. The advantages of using this style of transition duct are that it results in minimum aerodynamic losses, it provides a constant exit flow angle consistent with the vane and blade geometries, and it minimizes distortion in the exiting flow field.

The heated combustion gases would exceed the capabilities of the metal structure if no thermal protection were provided. To maintain the metal structure at an acceptable level, a thermal barrier coating and effusion cooling are incorporated into the mechanical design of the scroll.

The thermal barrier coating will result in a metal temperature significantly below that of the hot gas flow by virtue of the low thermal conductivity of the coating. Active cooling is provided by closely spaced effusion cooling holes that direct cooler air through the wall of the scroll into the hot gas flow path. This provides a film of cooler air that further reduces the temperature at the surface of the coating, and thus of the metal.

The structure of the scroll, while complex, can be produced via either casting or fabrication methods. The scroll is split to allow internal access for application of the thermal barrier coating, and for easier access for drilling of the effusion cooling holes. The scroll is being designed to meet specific goals for durability and ease of inspection and for refurbishment of the coating if required.

Evaluation of proposed methods of manufacture and of specifying materials to be used in the construction of the transition section are being analyzed as the design layout and detail drawing design activities continue. Final design layout definition is expected to be finalized in early 1998.

Key issues to be resolved prior to completion of the final design layout definition include:

- Method of manufacture
- Coating evaluation
- Drilling of effusion-cooling holes
- Materials selection
- Selection of suppliers
- Modifications to geometry necessitated by results obtained from sector rig testing

Powdered Metal Turbine Disks: One of the design trade-offs made in the ATS turbine was to assess which material to use for the high pressure turbine first and second-stage disks. U720 was selected because of space limitations at the bore and because of the high rim temperatures; Waspaloy would have required more axial width at the bore to have been a feasible candidate. U720 wheel forgings were quoted using a conventional cast-wrought process; however, in response to the relatively high cost of the forging, powdered metal (PM) was investigated as a possible lower cost alternative. Further cost evaluation indicates a recurring piece part

savings of 48% can be realized over a standard cast-wrought forging.

Although Allison does not have production experience with PM U720, development of PM disks was conducted as part of the U.S. Army's T800 program with great success. Allison is currently working to complete a probabilistic lifing program that is expected to be finished prior to ATS production. The use of PM provides the potential to reduce material and machining cost by progressing to a near net shape forging.

Ladish Co., Inc. of Cudahy, Wisconsin, will supply the initial PM U720 forgings for the ATS development program.

Ceramic Vane Design and Development: A major overall goal of the DOE Advanced Turbine Program is ultra-high efficiency. Ceramic turbine components offer the potential for increasing ATS turbine efficiencies (and power output) by decreasing turbine chargeable cooling flow requirements.

An objective of the DOE/Allison ATS Program is to evaluate and demonstrate uncooled ceramic vanes for the Allison ATS turbine. Ceramic first-stage vanes will be demonstrated at a commercial site in a current generation Allison 501-K industrial turbine as a stepping stone to introduction of uncooled ceramic, second-stage vanes in the Allison ATS engine. The peak gas temperatures, combustor pattern thermal gradients, and emergency shutdown thermal shock are expected to be slightly less severe for the ATS turbine second vanes compared to the 501-K turbine first vanes. Ceramic second-stage vanes will be designed, analyzed, and procured for insertion into the HP turbine and testing during two-spool runs of the ATS engine.

501-K Turbine Ceramic Vane Effort: The ceramic first-stage vanes for the 501-K turbine have been designed and analyzed. Acceptable stress levels have been calculated for maximum continuous power steady-state and emergency shutdown thermal shock conditions. Fast fracture probabilities of survival greater than 99.99% have been calculated at these conditions for vanes fabricated from AlliedSignal AS 800 Si3N4 ceramic. AS 800 specimens have survived exposures up to 8000 hr in stress rupture tests at Oak Ridge National Laboratories (ORNL) and the University of Dayton at the maximum calculated vane steady-state stress (172 MPa) and over 130°C higher temperatures (1316°C). Retained strengths after long-term exposure have exceeded maximum values (208 MPa) calculated in the vanes for emergency shutdown. AS 800 ceramic vanes and spares have been ordered for installation into a 501-K engine for proof tests at Allison and a field demonstration of up to 8000 hr.

ATS Turbine Vanes: Four candidate ceramic vane design concepts for the ATS engine were defined and presented to ceramic vendors for their comments on manufacturability and costs. The objective was to identify a vane design with the lowest practical cost; this was done to minimize cost issues at the early stage of commercial introduction before high volume production is achieved. The simplest vane design concepts were modifications of the 501-K ceramic vane simple design to accommodate cantilevered support from one end, compared to nonrigid support of the 501-K ceramic vanes from both ends. Relative cost estimates for initial small production quantities from the vendors did show a high initial cost sensitivity to design, with a factor of up to 2.6x difference in predicted manufacturing cost between the various concepts.

Analyses have started to define an airfoil shape for the ceramic ATS second-stage vanes. The ceramic airfoil must be thin enough

for uniform cooling during turbine emergency shutdown so thermal shock stresses are acceptable. The airfoil must also be thick enough that steady-state bending stresses from aero loads are acceptable. Approximate analyses indicate a factor of nearly five times greater steady-state bending moment for the ATS second vane compared to the 501-K first vane, even though the vanes are of similar scale. This is due to three times higher pressure ratio and aspects related to mounting requirements for second-stage vanes compared to first-stage vanes.

Aerodynamic analyses have defined candidate vane contours with acceptable aerodynamic performance, relatively small maximum-to-trailing edge thickness ratios for alleviation of thermal shock stresses, and increased moments of inertia (and stiffness) to resist bending loads. Screening thermal and stress analyses will be used to choose the airfoil shape for the ATS turbine second-stage ceramic vane.

Application: Elimination of second-stage vane cooling flows by use of ceramic vanes could result in about a 0.35% increase in overall engine efficiency and about a 670 shaft horsepower increase in output compared to the all metallic 701-K (ATS) turbine. Potential economic benefits to the owner of the 701-K turbine with uncooled ceramic second-stage vanes and corresponding increased performance were calculated.

System Integration

Overall success of the ATS program does not rest with the gas turbine system. Equally important is the integration of the turbine with the customer package. The generator package for the ATS field demonstration, and ultimately for commercial sale, is being designed concurrently with USTC.

Conceptual package design is in progress. This includes numerous design integration meetings to define installation requirements, gas turbine-to-package interfaces, and control system and support system interfaces. The complete package drive-line has been defined, which establishes the basic footprint of the system. This is the initial step and is central to establishing the overall package cost and efficiency.

APPLICATION

The Allison 701-K revolutionary simple cycle thermal efficiency in combination with the low emissions signature have a profound effect on fuel cost and the net system emissions compared with existing industrial gas turbines.

Operating cost and emissions between two simple cycle gas turbines, Allison's ATS and current/competing systems, were compared at an equivalent available power of 13 MWe. The thermal efficiency of the Allison ATS/701-K was assumed to be 40%, while an engine representative of the current industry standard was modeled at 35%. A general comparison of ATS technology to existing technology is shown in Figure 9. Both engines were assumed to have equal levels of emissions performance at 9 ppm NO_X and 20 ppm CO and UHC. To achieve the same equivalent power output, the engine representative of the industry standard (35%) would require increased airflow. The total airflow was 99 lbm/sec, compared with 86.8 lbm/sec on the 701-K18.

Both engines were evaluated for one year of operation or 8000 hr at the same natural gas fuel price of $3.00 per million Btu. The comparisons on annual fuel costs and emission levels are dramatic. Total annual fuel costs, in thousands of dollars, for systems ranging form
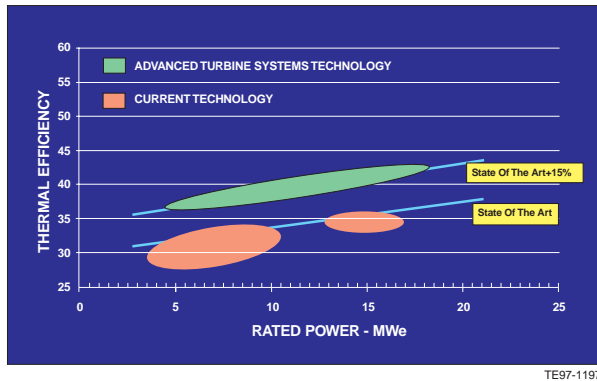
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Figure 9. ATS advancement over current state of the art.

30 to 40% in thermal efficiency are compared in Figure 10. When specifically comparing a 35% thermally efficient system with the ATS at 40%, the annual fuel savings of the ATS is estimated at $380,000 per year.

Emission levels are often compared on an instantaneous basis, and in this evaluation the ATS and currently available systems are compared at equivalent instantaneous emission performance levels. As a result, the less efficient system requires more net airflow to achieve the equivalent power. This necessitates more fuel burn, as shown in the fuel savings comparison, and thus a higher gross output of emissions. Tons of annual NO_x and CO_2 emissions for systems ranging
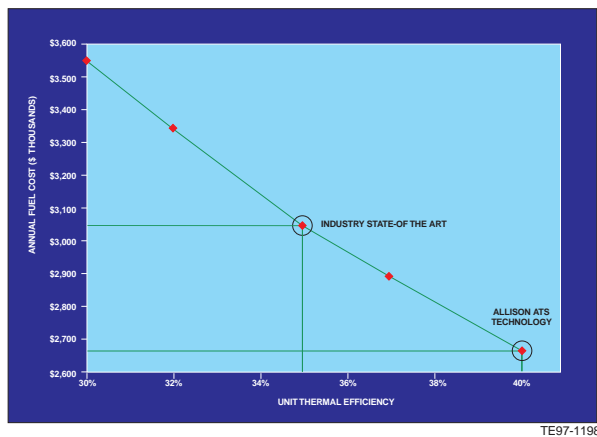
from 30 to 40% thermal efficiency are compared in Figures 11 and 12, respectively. When specifically comparing the Allison ATS to current systems at 35%, the annual NO_x and CO_2 emissions are reduced by approximately 0.9 and 5.8, tons, respectively.

FUTURE ACTIVITIES

Activities on the ATS Program will continue to expand over the next 12 months. The planned activities include:

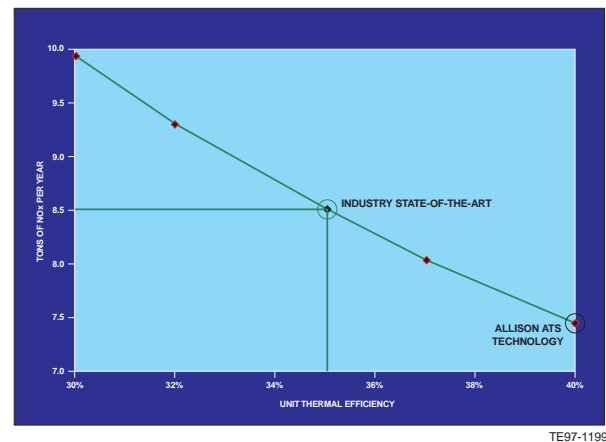- Completion of the gas turbine detailed drawing package

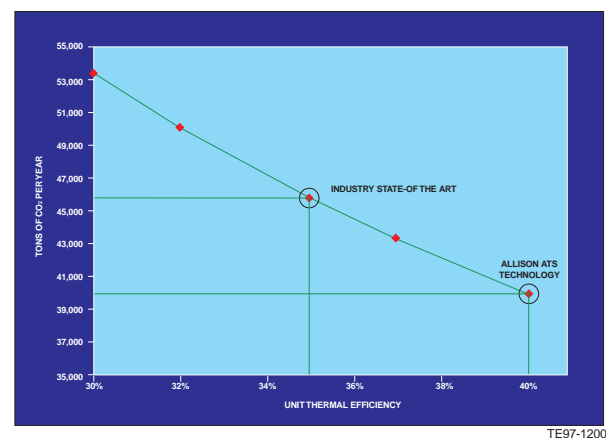Figure 11. ATS efficiency impact on NO_x mass emission.

Figure 10. ATS efficiency impact on fuel costs.

Figure 12. ATS efficiency impact on CO_2 emission.

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- Delivery of raw, castings, and forging materials

- Machining and fabrication of all long lead engine hardware in preparation for gas generator development testing

- Full-scale combustion rig design and fabrication LP compressor rig design, fabrication, and testing

- Continued subscale combustion testing and catalyst development

- Generator package detailed design and long lead hardware procurement

ACKNOWLEDGMENTS